THE INTERNAL ARCHITECTURE OF METALS.[1]

IT has been cynically remarked that to deliver a successful scientific lecture to a cultured audience it is necessary to divide the lecture into three parts. The first part should be understood both by the audience and the lecturer; the second part by the lecturer and not by the audience; and the third part neither by the audience nor by the lecturer.

If the foregoing dictum were true, the speaker found himself in a paradoxical position. The object of the discourse was to make the subject under consideration as clear as possible throughout, hence the more nearly this object was achieved, the more unsuccessful the lecture. The title of the discourse might seem to some far-fetched, since, superficially, a bar of polished brass or steel apparently presented the archetype of a homogeneous solid. Any such idea, however, must in a few moments be dispelled. Taking a section of pure gold, or at any rate of gold of a purity of 99·995 per cent., this, when polished and etched, presented under a low power of the microscope large allotrimorphic crystals, the etching figures of which exhibited varying orientation in different crystals. Hence (see Fig. 1) one crystal might appear black, another show the brilliant yellow of gold, and a third exhibit middle tone. All these were purely optical effects. In the black crystal the orientation was at such an angle as to reflect the light entirely outside the objective, whilst, going to the other extreme, the gold-coloured crystal had a molecular orientation which reflected the light entirely into the objective. It was well known that the addition of one or two tenths per cent. of the metal bismuth to gold produced a surprising mass brittleness which naturally led to the enunciation of theories to account for so remarkable a phenomenon.

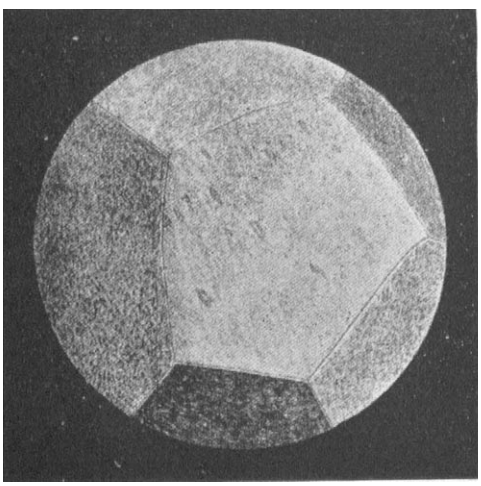

FIG. 1.—Gold.

Twelve years ago the theory which commanded a general acceptance, and at that time reasonably so, was that the small quantity of bismuth was incapable *per se* of producing so profound a mechanical change as to convert one of the most ductile of metals into a mass possessing an almost glassy brittleness. Therefore, the metal bismuth must act indirectly, its presence determining the maintenance of the molecules of gold in a brittle allotropic modification.

In 1896 there was published in *Engineering* from the laboratories of the Sheffield College an unambitious research recording the discovery of eutectic cements, which to a considerable extent altered the whole trend of metallurgical thought.

[1] Abstract of a discourse delivered at the Royal Institution on Friday, February 23, by Prof. J. O. Arnold.

Fig. 2 shows a micro-section of the structure of gold to which 0·2 per cent. of bismuth had been added. The microscope had at once explained the hitherto mysterious action of bismuth. It indicated clearly that the small quantity of bismuth alloyed with a definite amount of gold forming a constituent having a much lower freezing point than the main mass. Hence, when crystallisation set in during solidification from a series of centres, the "eutectic" or constituent last fluid was expelled to the exterior of each crystalline grain of pure gold, thus enveloping each crystal in a membrane of gold-bismuth alloy having a much higher coefficient of contraction than the crystal itself. Hence, during cooling, the gold-bismuth alloy, which may be regarded as the mortar of the structure, to a considerable extent detached itself from the crystalline grains of gold which may be regarded as the stones of which the mass is built up. In the micrograph, Fig. 2, the stones of tough gold are represented as white, whilst the mortar of gold-bismuth eutectic is shown as dark, thick, enveloping membranes. These membranes become pasty well below a red heat, and it was proved that at 400° C. the mass could be powdered in a mortar, the crystalline grains of pure gold becoming detached from the feeble alloy cementing them together. One of these crystalline grains exhibited no signs of the brittleness of the mass from which it was thus detached, but was readily beaten out into gold leaf in the ordinary manner.

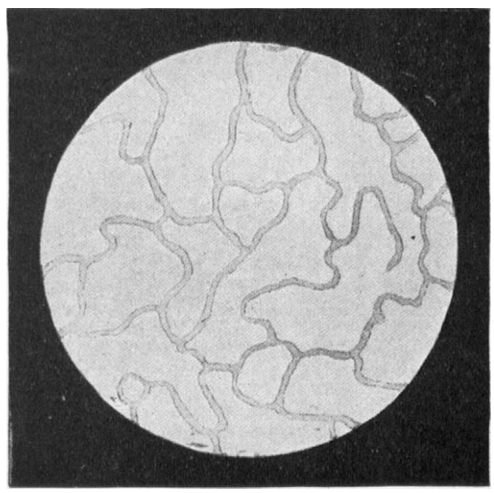

FIG. 2.—Gold containing 0·2 per cent. of bismuth.

Passing from gold to brass, it was proposed to diverge from the abstract to the concrete, and to show the value of the application of the science of metallurgy to practical problems connected with mysterious failures in marine engineering.

A notable case in point was the explosion of the brazed copper main steam-pipe of the s.s. *Prodano* in calm weather off the Kentish Knock at a pressure about one-tenth of that to which it had been previously tested. In this case the microscope was again successful in clearly indicating the nature of the electrolytic decay, under certain conditions, of brass used in naval architecture. In this connection, a familiar phenomenon is the decay of Muntz metal bolts exposed to the action of bilge water. Such bolts break suddenly, and present a distinctly coppery fracture. A micrographic examination of such bolts usually revealed a minor area of undeteriorated brass and a major area of deteriorated brass—that was to say, brass which had been more or less dezincified, an expression which meant, in other words, that the mass had become transformed into rotten, spongy copper.

Brass often consisted of two constituents, namely, a ground mass of true brass of formula Cu_2Zn and a eutectic corresponding to the formula Zn_2Cu. Upon a mass so constituted a feeble saline electrolyte attacked in

the first instance the constituent rich in zinc, whilst the constituent rich in copper assumed an electronegative position, acting, of course, as the kathode of the couple.

But, when the eutectic had been transformed into spongy copper, the latter assumed the electronegative position and the true brass became the anode, hence gradually transforming the whole mass from Muntz metal into spongy copper. In the case of the *Prodano*, the electrolyte was proved beyond all doubt to have consisted of fatty acids due to the use of improper lubricants. Little by little the brazed seam was cuprified until the junction became so weakened that at a pressure of only 130 lb. per square inch the port main steam-pipe opened for a space of 6 feet and consigned four men to an agonising death.

This research, made at the Sheffield College under instructions from the committee of Lloyd's Register, resulted practically in the abolition of brazed copper main steam-pipes, and in the substitution of rolled steel ones.

Reaching the third section of the lecture, this undoubtedly must be regarded in the steel age as the most important, since it dealt with steel. Taking the base of steel, namely, pure iron, this had a similar structure to that of pure gold, but the etching figures exhibiting the molecular orientation in the allotrimorphic crystals of this metal were seldom revealed by ordinary etching.

Broadly speaking, iron was converted into steel by the addition of the element carbon, and researches made in the Sheffield College indicated that steels naturally divided themselves into three classes, namely, unsaturated, saturated, and supersaturated steels. If 0·3 per cent. of carbon were added to steel, the carbon converted one-third of the iron into the constituent pearlite, and in such a steel, as cast, the iron or ferrite frequently arranged itself into a pattern, indicative of cubic crystallisation exactly comparable with the figures observed by Widmanstätten in the non-terrestrial steels called meteorites. In saturated steels, just sufficient carbon, approximately 0·9 per cent., had been added to the ferrite to convert it totally into the constituent pearlite, a definite mixture corresponding to the formula ($21Fe+Fe_3C$). This definite mixture presented at least three well-marked phases having different mechanical properties determined by the state of the division of the carbide Fe_3C. These phases might be differentiated by distinguishing the involved carbide as emulsified, normal, and laminated, the latter being the pearly constituent of Sorby, presenting a play of gorgeous colours, determined by the varying thickness of the laminæ acting like mother-of-pearl in nature, or the interference grating in science. Through no scientific foresight, but, as a matter of fact, by an act of carelessness, there had been secured at the Sheffield College a section showing the transformation of pearlite into hardenite in the most perfect manner yet recorded. The two constituents, pearlite and hardenite, might humanly be described as the most important in nature, since upon unhardened and hardened steel depended the remarkable triumphs of the civil, the mechanical, and the electrical engineer.

The quartz-hard transformation product of pearlite discovered by the versatile genius of Dr. Sorby itself presented what might be termed effective and futile phases, dependent upon the temperature of quenching. In properly quenched steel, the accidental section before referred to showed that at a moderate temperature the transformation proceeded, not suddenly, but from a series of converging centres, until the whole mass consisted of the obsidian-like substance, structureless hardenite. At too high a temperature this steely obsidian developed decisive cubic crystallisation, recorded in the micro-structure by equilateral etching figures indicative of ruined steel. In supersaturated steel in the unhardened condition, the cells of pearlite were environed by brilliant walls of cementite, Fe_3C, which in hardened steel enveloped similar cells of hardenite, corresponding to the empirical formula $Fe_{24}C$.

Of the three broad types of steel described, by far the most important was unsaturated steel, a synonymous term for which was structural steel, embracing boiler-plates, ship-plates, bridge-plates, rails, and the gigantic engine parts which formed the backbone of our battleships and cruisers.

To show the enormous importance of the scientific study of this class of steel, it was well to indicate, not only its failure, but after brilliant service, also that of the microscope scientifically applied.

The figure thrown upon the screen was that of a boiler, which might be described as several sorts of boiler. It was a marine boiler, a cruiser's boiler, and possibly a mad boiler—it was, at any rate, cracked. Fortunately this rupture occurred before the cruiser was put into commission, and a defect in the steel which might have resulted in a catastrophe was detected by an extra inspection after the boiler had been impressed with the Government pass mark. The chronology of the testing operations was recorded in the following table:—

Date		Nature of pressure	lb. per sq. in.
February	5	Hydraulic	228
,,	8	,,	260
,,	19	,,	305
,,	20	Steam	60
,,	21	Hydraulic	270 (burst)

The mechanical tests of the boiler-plate steel which had thus failed left little to be desired, and the same remark applies to static mechanical tests taken along the line of fracture. Micrographic tests indicated that the steel presented marked features of inferiority when compared with undoubtedly good boiler-plate steel. Superficially the matter was thus solved, but, under alternating or dynamic stress tests, slightly beyond the elastic limit, the steel registered tests varying from 230 to 1292 alternations. The most disconcerting feature in these astoundingly divergent tests was that the test bars registering them were identical in micrographic structure.

At the Cambridge meeting of the British Association, the lecturer suggested that these divergent tests must be associated with opposite sides of the plate subjected to varying heat treatment. The lecturer was quite wrong; and, after twenty-five years' experience, had failed to realise the fact that in connection with steel one must often expect the unexpected.

Remarkable failures in structural steel were commonly associated with the phenomenon called "fatigue." What was "fatigue"? Some little time ago, in an important naval trial at the King's Bench, counsel requested the lecturer to define for My Lord the meaning of this term, which had frequently occurred during the trial, and which he failed to understand. Unfortunately the lecturer also was involved in the outer darkness of My Lord on this matter, but was compelled to give "fatigue" at that time a definition, which remains substantially true to-day, namely, that he regarded "fatigue" as a generic term used clearly to explain all cases of fracture which were not understood. Before venturing to suggest an explanation for these mysterious fractures, for which popular blame often fell upon men who were doing their very best, he would ask his hearers to imagine that that small cloud, no bigger than a man's hand, now hovering over the North Sea, should burst in storm, and that our armour, our guns, and our armour-piercing shells should be put to the stern implacable test of actual warfare. Supposing our guns were faulty, our shells failed to penetrate the armour of the enemy, our armour was incapable of protecting the gallant inmates of our battleships; assuming this hypothesis, which the lecturer believed to be totally untrue, what would all this mean? It would mean that the internal architecture of British wrought steel was all wrong, and the interesting question thus arose, who were the men responsible for the internal architecture of these metals? The lecturer knew them well. They were grave-eyed men with set mouths, who, week after week, month after month, and year after year, lived and moved, and had their being, and sometimes died, amid the flare of gigantic furnaces and the rattle of Titanic rolls, steadfastly working upon those metals which formed Britain's first line of defence, and to-night, on behalf of these inarticulate men, the lecturer confidently asked his distinguished audience to exclaim in their hearts, "These men have deserved well of their country."

Reverting to the remarkable and disconcerting fact that two pieces of the faulty boiler-plate steel of identical structure, so far as could be seen by the microscope, gave astoundingly different results under dynamic stresses, the

lecturer put forward as a tentative hypothesis the theory that, underlying the gross and visible micro-structure of the steel, there existed a molecular structure, which in the present state of knowledge could not be detected, except in rare cases, by the microscope. It was suggested that this molecular structure was brought about by improper heat treatment developing in the ferrite from a series of centres well developed mineral cleavage. On the circumference of these centres existed areas in which the molecular cleavage was less perfectly developed, and beyond these were the areas of good steel in which the cleavage lines were extremely imperfect. It was then easy to conceive that the plane of dynamic fracture in a perfectly developed cleavage area might give the remarkably low record of having endured only 230 alternations, as in the table previously exhibited on the screen, whilst a test-piece in which the plane of fracture went through an area of good steel free from what might be called cleavage disease might readily endure 1290 alternations before breaking, and a third test-piece from the middle zone of somewhat developed cleavage might endure, say, 700 alternations. This theory, at any rate, was in accordance with the mechanical facts which had been presented. Another step towards the experimental verification of this hypothesis would be to prove that iron was a veritable mineral, as capable of exhibiting geometrical cleavage as was, say, fluor-spar or Carrara marble. Fortunately the lecturer

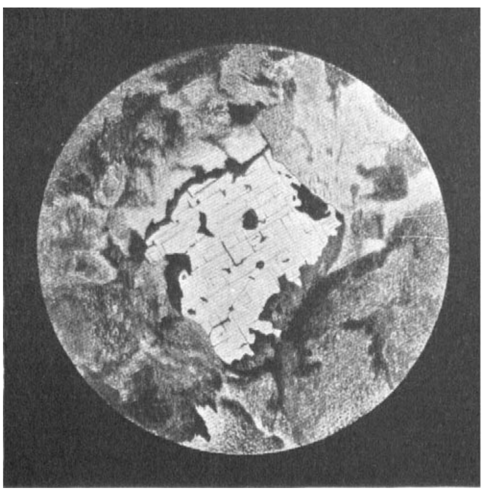

FIG. 3.

found himself in a position, by what might be called a million-to-one chance, clearly to prove that iron could possess absolutely perfect mineral cleavage parallel to the faces of the cube. This discovery came in no heroic form from the swift-moving machinery of a destroyer or in connection with metal forming the stupendous engines of a battleship, but in connection with a wrought-iron bolt, literally forming part of a common or garden gate-post. This fractured under the taps of a hand-hammer during repairs, and one of the crystals cleaved exactly at right angles to the axis of the bolt, and consequently when the fractured end was cut off in the lathe for examination, it was found at right angles to the axis of the microscope, exhibiting the wonderfully perfect cubic cleavage delineated in Fig. 3.

Metallurgists had now arrived at a deadlock. The microscope, after rendering great services, had in its turn broken down, mainly owing to the fact that optical examinations associated with transmitted light could not be applied to opaque objects, and in more senses than one the scientific metallurgist could not yet see through steel. Nevertheless, he must endeavour to tear down this mysterious veil or in some way get behind it, and in the lecturer's opinion the resources of science in connection with steel metallurgy were not yet exhausted.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

MR. A. C. SEWARD, F.R.S., has been appointed professor of botany in the University of Cambridge in succession to the late Prof. Marshall Ward.

WE learn from *Science* that Mr. J. A. Creighton, one of the founders of Creighton University, Omaha, Nebr., has presented to that institution two buildings worth about 100,000*l*.

AN interesting educational development in Manchester is recorded in the *Electrician*. The Corporation of that city has just decided to take approved students from the School of Technology into the electricity works for a three years' training, giving them a certain small but increasing salary during that time. This privilege is to be restricted to sons of Manchester ratepayers.

IT is announced in *Science* that Mr. A. C. Chapin has given Williams College an additional gift of 10,000*l*., to be used by the trustees without restriction, and that Mr. C. T. Barney has given 2000*l*. to the college. It is stated that the fund for Oberlin College, as completed, amounts to 100,300*l*. This includes the following funds:—25,000*l*. for a new library building given by Mr. Andrew Carnegie, 20,000*l*. for library endowment, 20,000*l*. from an anonymous donor in Boston for the increase of salaries of teachers in the college and seminary, and 30,000*l*. for miscellaneous purposes. The gift of the Boston donor enables the trustees to increase by 40*l*. the salaries of twenty-four full professors.

THE following announcement appears in the volume of Regulations (Cd. 3201) just issued by the Board of Education containing the prospectus of the Royal College of Science, London, with which is incorporated the Royal School of Mines (session 1906–7):—"It is probable that as a result of the investigation made by the departmental committee lately appointed by the President of the Board of Education, various changes will be made in the organisation and relations of the Royal College of Science, including the Royal School of Mines. The Board therefore give notice that the arrangements detailed in this prospectus are subject to such alterations as they may determine in respect of the classes for the college session, 1906–7, and of courses of study in future."

THE last report of the Scotch Education Department dealing with secondary education in Scotland directs attention to a new departure in the method of awarding leaving and intermediate certificates. The report states that last year the aid of the teacher was actively enlisted in determining the question of success or failure, and that much weight was attached to a pupil's school record, as properly attested by his teacher, in the allocation of school bursaries. The secretary puts it on record that events have completely justified the confidence of the Department. The teachers, as a body, have risen to the responsibility that was placed upon them. Of course there were cases of miscalculation by the teacher, but these were rare exceptions. The success which this Scottish experiment has met in the direction of humanising the methods of appraising knowledge and intellectual training, with the object of selecting the best pupils, should encourage those responsible for examinations south of the Tweed to increase their efforts to abolish the mechanical character of many of the current tests to which young students are subjected.

THE annual general meeting of the Association of Teachers in Technical Institutes was held on Saturday, October 27. Mr. W. J. Lineham, president, occupied the chair, and Mr. V. Mundella was elected president for the ensuing year. The following resolutions were adopted:—(1) That the association urges the desirability of attendance at evening continuation schools between the ages of fourteen and sixteen being made compulsory upon all not in attendance at elementary or secondary schools. (2) That in view of the generally inadequate provision made in the present scholarship schemes of local educational authorities for the needs of scientific, technological, and trade students, the local branches of the association be instructed to consider what amendments of local scholarship schemes